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Onboard Autonomous Response for UAVSAR as a Demonstration Platform for Future Space-Based Radar Missions

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Abstract. The paper discusses software to enable: 1. onboard processing and interpretation of radar data and 2. autonomous response to retask vehicle and instrument based upon interpretation of this data. We first discuss scenarios in which space-based radar could benefit from this autonomous interpretation and response capabilitiy. Next we discuss the Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) airborne testbed and its use as a surrogate for a spaceborne testbed. We then discuss a range of onboard processing products that have been investigated and produced onboard. We then discuss the retasking model and process for UAVSAR. We discuss a flight demonstration of the onboard data processing and retasking that occured in January 2012. Finally we discuss related work and areas for future work.

1 Introduction

Space based radar has been found to have a wide range of science and humanitarian applications [1, 17] including but not limited to: vegetation and ecosystem studies [2, 5, 14], wildfires [13], flooding, soil moisture, and hydrology [16, 21], solid earth (earthquakes, landslides, volcanoes) [3, 19, 22] and cryosphere (glaciers, climate change). NASA and other space agencies have flown a number of missions that provide this space-based radar capability for these science and applications areas. These missions include but are not limited to RADARSAT-1 and RADARSAT-2 (Canadian Space Agency), TerraSAR-X and TanDEM-X (German Space Agency), ALOS/PALAR (Japanese Space Agency), Shuttle Imaging Radar (National Aeronautics and Space Administration), Envisat/ASAR (European Space Agency). These same agencies are also studying possible future missions to provide this unique capability for science and applications.

Synthetic aperture radars utilize the flight path of the instrument to synthesize a large aperture to form radar/backscatter images of the earth. Interferometric processing of radar images can utilize multiple instruments or multiple overflights to synthesize altimetry and/or change data for a surface. Below we show a sample UAVSAR image acquired of a glacier in Greenland from June 2009 (Figure 1) and a change detection interferogram product showing land displacement in Baja California from October 2009 to April 2010 (Figure 2).

One challenge of space-based imaging radars is that radar data can be extremely large. Onboard processing offers several advantages over traditional ground-based processing. Onboard products can be used to deliver much smaller notifications (alerts) and or summary products to ground personnel and assets using more convenient data low capacity links. Onboard prod-

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Figure 1: Image of Greenland Glacier acquired by UAVSAR in June 2009. Image courtesy JPL/NASA.

ucts can be used to retask the acquiring asset or other assets to acquire followup imagery. Analysis of the onboard products can be used to selectively not downlink or delete the full aquired imagery, thereby relieving storage and downlink resources.

In the remainder of this paper, we describe efforts to develop and demonstrate the capability to develop radar products onboard and retask assets based on interpretation of these products.

2 The Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR)

The UAVSAR is an airborne platform developed by NASA to study earth science and emergency response potential [11] using remote sensing radar. UAVSAR is a Gulfstream-III jet with the radar mounted in a pod below the fuselage (see Figure 3). While UAVSAR is a piloted aircraft it is intended as a precursor testbed to the deployment of the UAVSAR radar onto unpiloted aerial vehicles as well as space vehicles.

Within the UAVASAR aircraft computers and instrument processing hardware are mounted to enable onboard processing of the radar imagery. Onboard general purpose computing hardware are also used for onboard image/product analysis and retasking the UAVSAR. The onboard processing hardware is shown to the left of the aisle in the image in Figure 4 below.

Special purpose cards (shown below in Figure 5) including field programmable gate array (FPGA) capability are used to process the radar images in near real time.

3 Autonomous Response Scenario: Space-Based Radar and Airborne Radar

Enabling onboard interpretation and response has many applications for space-based and airborne radar. In each case the first step is to form the radar image. Luckily, for our onboard autonomy work, the UAVSAR project has been addressing exactly this challenging task [15]. Onboard the UAVSAR, the raw radar data is streamed to recorders and is simultaneously streamed to the *Onboard Processor* which forms the synthetic aperture radar image. This radar image can be formed in a range of polarizations (e.g, HH, HV, etc.). Once the radar image is formed, the backscatter image data can be interpreted using application-specific algorithms. Based on the mission at hand, this interpretation can then be used to direct future operations of the space or air vehicle. For space-based radar, applications of onboard autonomy abound. For example, detection of volcanic activity by detection of ash emissions might trigger followup imagery on a later orbital overflight. Or mapping of the flooded area might be used to direct the same or different radar to acquire higher resolution imagery of the boundary of the flooded area. Or the same area might be imaged on a subsequent overflight to map out a timeseries of the progression of the flood. Alternatively, biomass analysis might be used to map out the progression of a forest fire. All of these scenarios involve the same baseic operations pattern of:

- form radar image
- analyze radar image
- generate new target requests
- assimilate new target requests into operational plan as appropriate based on prioritization.

These scenarios are highlighted by the operations flow in Figure 6.

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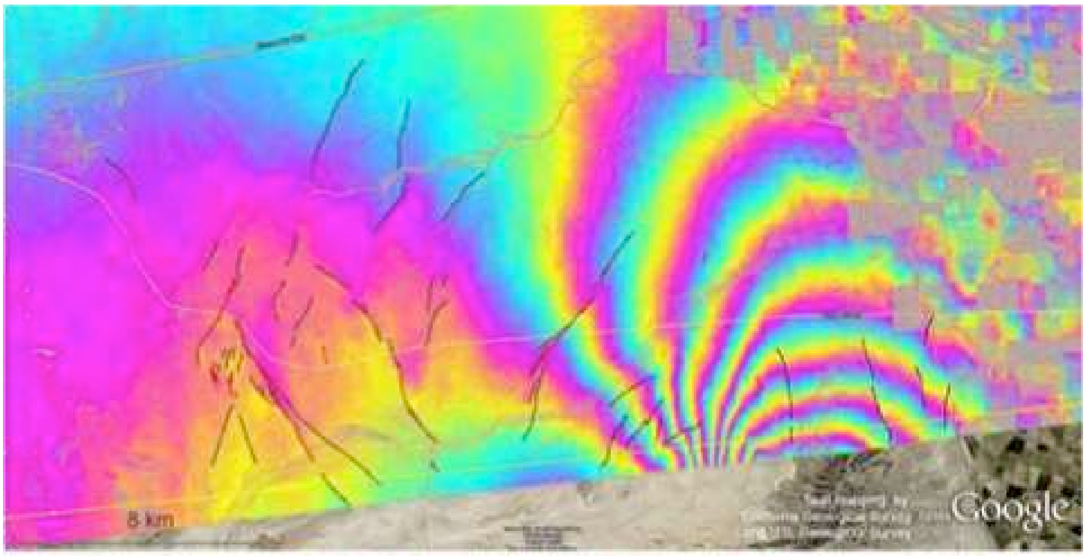

Figure 2: Interferogram showing displacement (change) from an earthquake in Baja California, Mexico. First image acquired in October 2009. Second image acquired in April 2010. Black lines indicate interpreted faults and red lines show where geologists in the field confirmed surface rupture. Image courtesy NASA JPL/United States Geological Survey/California Geological Survey/Google.

4 Onboard processing of radar imagery

Once the SAR image has been formed [15] it can be used as the basis of interpretation for many science and application purposes [7, 8]. The multiple available polarizations contain significant information that can reveal surface smoothness properties, structure properties, as well as water content/moisture properties of the substances being imaged. While interferometric analysis can also provide tremendous amounts of data for many targets, since our autonomy thus far has focused on individual overflights (and UAVSAR cannot do single pass interferometry) we have focused on SAR imaging capabilities. The table below in Figure 7 shows a number of onboard processing analysis products that have been considered in this and other efforts.

In our specific autonomy demonstration, we used an amplitude segmentation algorithm that is sensitive to changes in surface roughness/smoothness features of the surface being imaged. This algorithm is useful for detecting differences in the substance being imaged (e.g. liquid versus solid land) as well as covering layers (e.g. oil on the surface of water). This algorithm consists of a number of processing steps.

- Each base image is multilooked/subsampled at different resolutions into a stack of images. The remaining procedure's results will vary with the incoming resolution due to pixel-to-pixel value variation and/or perceived sharpness of edges in the image.

- Each subsampled image is then segmented using a Felzenswalb/graph based segmentation routine, which generates a minimum spanning forest over the 4-neighborhood graph of pixel-magnitudes. This step is nearly linear run-time on the image size. This step produces regions/super-pixels of similar radar response that can be measured in area-of-coverage, geographic location, average intensity, and other statistical quantities.

- The resulting regions/segmentations are checked for "interest" criteria, such as minimum size, and in the case of our "oil-slick" demonstration, an average backscatter intensity below a tunable threshold (-28db).

- The stack of segmentation images are expanded to the greatest common resolution and a composite (pixel average) image is created as a highly compressible image containing qualitative visual features at various scales.

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Figure 3: The UAVSAR aircraft. Note the radar mounted in the pod directly underneath the fuselage

Figure 4: The interior of the UAVSAR aircraft. The rack to the left of the aisle is the rack for the onboard processing equipment.

Below in Figure 8 we show images of the Deep Horizons oil spill in the Gulf of Mexico along with the corresponding products processed with a range of segmentation scales.

5 Demonstration of onboard autonomy on UAVSAR

In this section we describe the autonomy software onboard the UAVSAR and its use in an onboard autonomy demonstration in January 2012. In this demonstration the UAVSAR successfully executed a number of steps.

- processed radar data into SAR imagery,
- autonomously analyzed the imagery,
- derived new observation goals from this analysis,
- developed a new flight plan to achieve the new observation goals, and
- when concurred by the radar operator and pilot UAVSAR flew the new flight plan to achieve the observation goal.

5.1 UAVSAR Autonomy System

The UAVSAR Autonomy System consists of a number of modules which are described below.

- The **OnBoard Processor** (OBP) takes a stream of the radar instrument raw image data and also data indicating the position, orientation, and velocity of the aircraft derived from GPS and inertial navigation unit (INU) data. It uses this information to form the SAR image of the relevant area of ground underneath the aircraft. The OBP can form images of various polarizations as needed by the subsequent analysis (e.g. HH, HV).
- The **Onboard Analysis** (OA) module is responsible for interpreting the formed SAR image. In our specific demonstration we utilized a surface smoothness analysis algorithm. The Onboard Analysis software takes the formed radar polarization and/or backscatter image and produces the analysis product.
- The **Target Generator** (TG) software uses the analysis product to generate new observation goals

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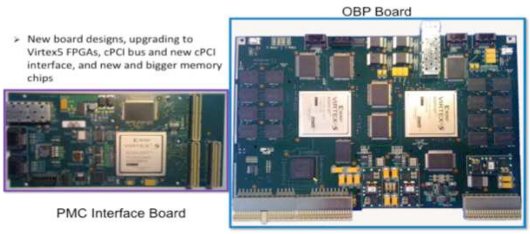

Figure 5: Closeup of the onboard radar processing cards.

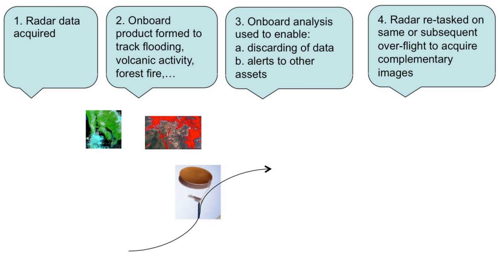

Figure 6: Autonomous interpretation and response scenario for space-based radar

for the planners to achieve. In our demonstration, the TG analyzes the imagery and selects smooth surface targets for followup imagery. For each area greater than a threshold size and smoothness, it generates a Point of Interest (POI) which in effect is an observation goal to image the area.

- The **Flight Line Analyzer** (FLA) takes the current flight plan and new observation goals (POIs) and first checks if all of the newly requested observation goals are achieved by the existing flight plan. If not, it selects a new flight line to propose for addition to the flight plan that covers the highest priority new observation goal. This new flight line is then submitted to the Flight Planner below.

- The **Flight Planner** (FP) attempts to add the new flight line to the current flight plan. It uses the Solomon insertion heuristic that tries insertions of the new flight line into the existing flight plan that minimize the makespan (total duration) of the resultant schedule.

- The **CASPER Planner** (CP) is a time, state, and resource planner that has been applied to a range of mission planning applications including onboard spacecraft control [6], rover control [9], aerobot control [10], and autonomous underwater vehicle planning [20]. CASPER is used to model UAVSAR operational constraints as well as deadlines. If the new flight plan passes these constraints modelled in CASPER it is passed on to the Radar Operator Workstation.

Algorithm	Applications	Notes
Soil moisture	Agriculture, Water resource management	Currently requires sparse vegetation; generalization of algorithms to variable/ dense vegetation future work.
Surface water extent	Flood mitigation	Extensions to varied topography, rough waters, and smooth land are future work.
Repeat-pass disturbance	General	Requires expert/interpreter and prior imagery onboard.
Snow/ice vs. land SVM classification	Transportation, Freeze-thaw monitoring	Vegetation can complicate classification.
Amplitude Correlation	Sea transportation, Glacial movement monitoring	Strong transportation application if provided repeat-pass data at rates of ~1hr. Glacial studies would desire higher fidelity (sub-pixel motion, per pixel).
Biomass	Wildfires, Invasive species, avalanche, blowdown, landslide, subsidence, tsunami	

Figure 7: A number of potential onboard radar products and their applications.

- The **Radar Operator Workstation** (ROW) manages the radar for the data acquisitions and also serves as the interface to the autopilot. The ROW receives the new CASPER-approved flight plan from CASPER and at the ROW the human radar operator can approve the flight plan for submission to the UAVSAR autopilot.

- The **UAVSAR Autopilot** (UA) actually flies the flight lines to the tolerances required by the UAVSAR SAR instrument. The UA receives the new flight plan from the ROW and allows the pilots to view the new flight plan. The pilots then review and accept or reject the new proposed flight plan. If the new flight plan is accepted then the autopilot (and UAVSAR) will then fly the new flight plan (including the new flight line for the new observation goal).

This operations flow is detailed below in a flowchart in Figure 9.

5.2 Autonomy Demonstration

In January 2012, the UAVSAR autonomy system was exercised in a flight demonstration. In this flight, an

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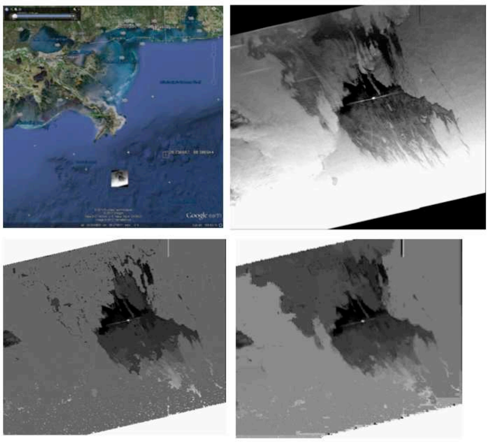

Figure 8: Oil Detection/Amplitude Segmentation Analysis Product on Gulf Of Mexico Oil Spill data. Upper Left: Context image showing location of oil spill south of the Mississippi delat in the Gulf of Mexico. Upper Right: Original browse image of HH polarization backscatter. Lower Left 60m segmented image Lower right: 60m composite image.

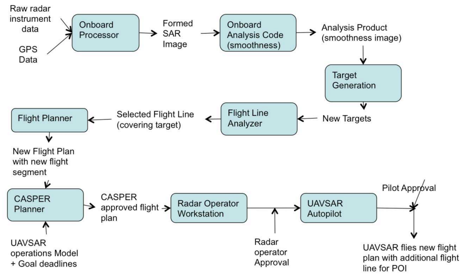

Figure 9: The operations flow for onboard processing and retasking the UAVSAR.

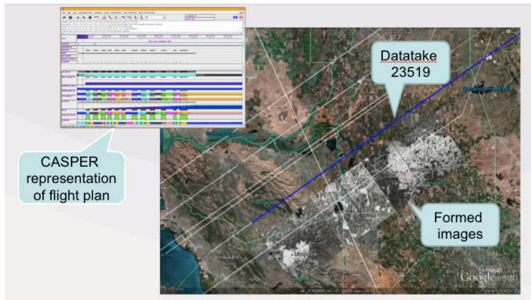

Figure 10: UAVSAR flies the original flight plan and acquires data according to plan. The Onboard Processor forms images as shown.

initial set of points of interest (POI's, e.g. areas to observe), flight plan of flight segments and CASPER plan was loaded into the UAVSAR autonomy system. As the UAVSAR flies the flight plan, it takes observations according to the plan and the Onboard Processor forms the radar images as shown in Figure 10.

As per the original plan, the Onboad Analysis Software also generates the Amplitude Segmentation product with the corresponding detections for each newly acquired image. These producs are shown in Figure 11. Using these products, the Target Generator generates a new observation goal for each detection. The Flight Line Analyzer then checks each of these new observation goals against the planned flight lines remaining in the current observation plan. Any goals that are not covered by existing segments in the remaining plan are flagged and the Flight Line Analyzer searches for flight lines in the current catalogue to cover these observation goals. For operational reasons all flyable flight lines must be pre-filed before flight, therefore preventing the flight line analyzer from creating novel flight lines.. In this case a flight line is found that covers the new observation goals. The Flight Planner (FP) then sequences the additional flight segment into the remaining plan minimizing overall flight time. This proposed plan is then sent to CASPER which validates that the plan does not violate UAVSAR operations state, resource, and flight deadline constraints. CASPER also includes new processing and analysis goals for the new data acquisitions. The CASPER Graphical User Interface is shown in Figure 12 displaying the CASPER plan including the new flight line.

Next, the CASPER validated plan is passed onwards to the ROW for radar operator approval. Once this is complete, it is passed on to the Autopilot where after pilot review it is accepted and the new plan is flown by the UAVSAR. This successful flight demonstration illustrates how the UAVSAR can be operated in a highly autonomous fashion to close the loop of data acqusition, analysis, and retasking.

6 Discussion and Conclusions

6.1 Related Work

Considerable work has focused on Unpiloted Aerial Vehicle path planning either for single or multiple vehi-

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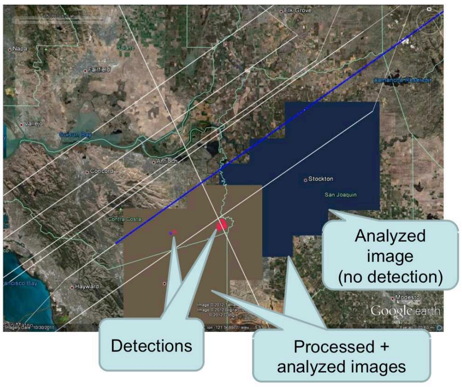

Figure 11: UAVSAR Onboard Analysis Software generates analysis of image. Target Generator then produces observation goals for new detections.

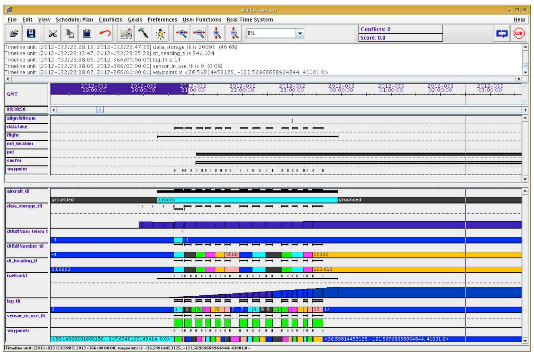

Figure 12: CASPER validates that new flight plan does not violate UAVSAR state, resource, and timing operational constraints and obeys UAVSAR flight deadlines.

cle configurations [18, 12, 4]. However this work has generally started with inputs that are waypoint goals. In contrast, this work has focused on integration of complex instrument data interpretation into the overall onboard autonomy including timing, resource, and path planning constraints (while not incorporating more complex path planning constraints such as avoidance zones, maneuvers, uncertain terrain, and other constraints).

6.2 Conclusions

In this paper we have described an overall approach to mission autonomy designed for space and airborne radar platforms. In this approach, onboard hardware and software is used to enable onboard processing of radar data into images and then to analysis products. These analysis products are used to drive generation of new observations goals, such as to enable tracking of dynamic phenomena such as flooding, oils spills, wildfires, or lava flows. Onboard flight planning, and state, resource, and deadline mission planning are then used to replan current mission and flight plans to accomodate these new goals as priorities warrant. This overall closed loop control enables more rapid response to capture key science and applications data for fast moving science and applications phenomena.

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